Lecture 1

Introduction to Distributed Generation (DG)

Objectives and Outlines

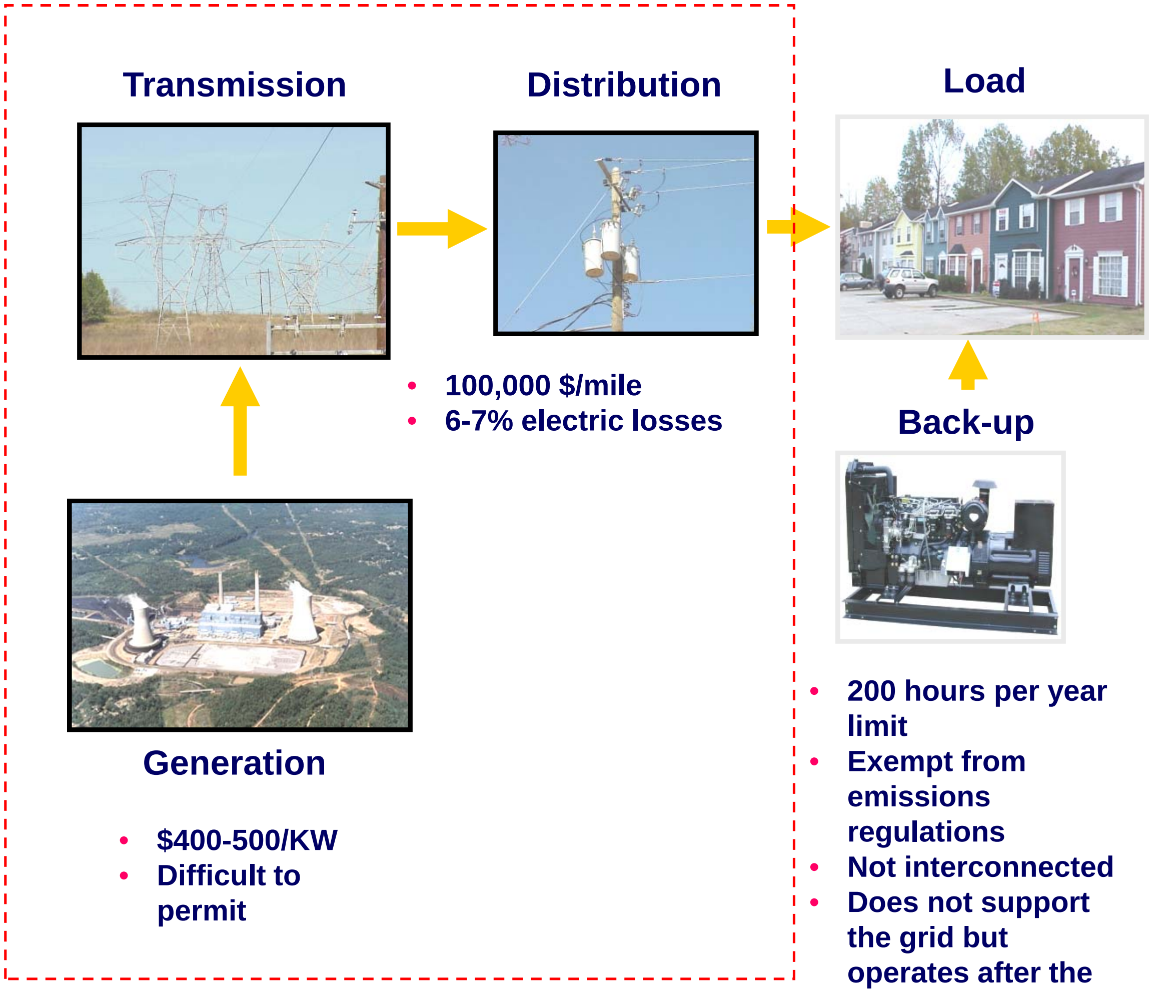
- Power Systems Structures.
- Definitions for Distributed Generation.
- Why Using DGs?
- Distributed Generation Characteristics.
- Impacts of Distributed Generation.
- Distributed Generation and Green Energy Statistics.
- Ontario’s RFP for Green Energy.
- Overview of DG Interfacing Equipment

Power Systems Structures

Conventional Electric Utility Service

Disadvantages:

- High power losses
- Service Reliability
- Quality of Service
- Permits for construction of infrastructure
- Environmental impacts and emissions



Transmission

Distribution

- 100,000 $/mile
- 6-7% electric losses

Load

Generation

- $400-500/KW
- Difficult to permit

Back-up

- 200 hours per year limit
- Exempt from emissions regulations
- Not interconnected
- Does not support the grid but operates after the grid has failed

Regulated

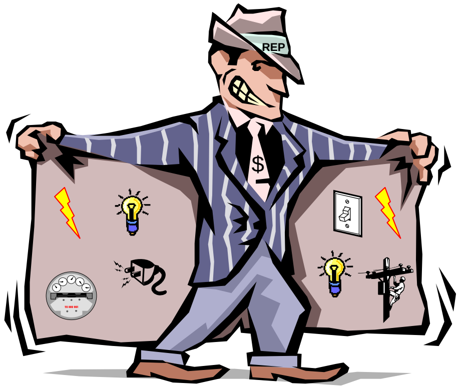
Restructured Electric Industry

Competitive Generation

Transmission & Distribution

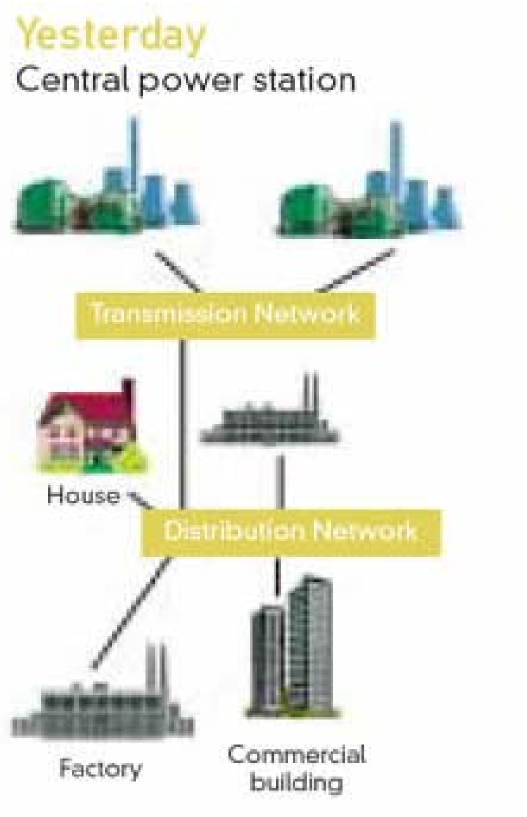
Regulated

Competitive Customer Service (Retail Electric Providers)

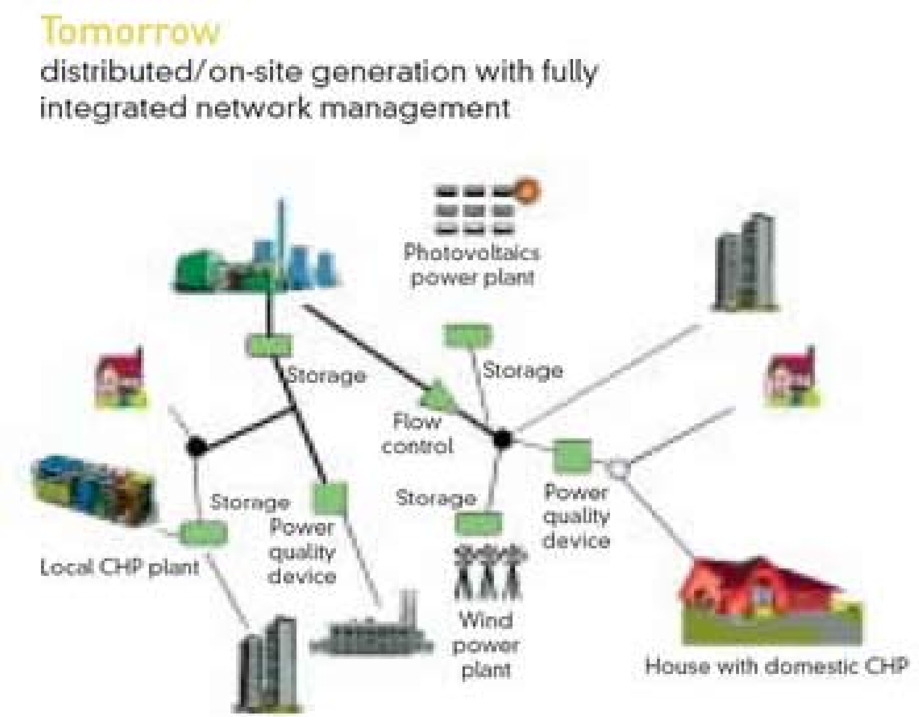


Customer

Centralized vs. Deregulated Structures


Yesterday
Central power station
Transmission Network
House
Distribution Network
Factory
Commercial building

Centralized
[22]


Tomorrow
distributed/on-site generation with fully integrated network management
Photovoltaics power plant
Storage
Storage
Flow control
Storage
Power quality device
Local CHP plant
Storage
Power quality device
Wind power plant
House with domestic CHP

Deregulated
[22]

Drives for Deregulated Environment

- Privatization.
- Regulation provided no incentives for innovation.
- Competition will improve customer focus.
- Cost is expected to drop

Deregulation Consequences

- Cost becomes an important issue in the competitive market.
- Customer satisfaction becomes important.
- Utilities should be capable of providing different power grades to be competitive.
- ***Allowing Independent Power Producers IPP to hook their generators on the grid (Distributed Generation)***

Obligations

- Efficiency
- Reliability
- Quality

All three factors can be achieved by allowing Distributed Generation (DG) to be connected to the grid.

Definitions of Distributed Generation

- There is no common, agreed upon, definition for distributed generation as confirmed by the International Conference of Electricity Distributors (CIRED) in 1999, on the basis of a questionnaire submitted to the member countries.

- Diversities in the definitions from one country to another depend on the definition bases such as [18]:
  - *Voltage level.*
  - *Unit connection.*
  - *Type of prime mover, e.g. renewable or co-generation (CHP).*
  - *Generation not being dispatched.*
  - *Maximum power rating.*

DG Definitions

- The International Council on Large Electricity Systems (CIGRE) (WG 37 – 23) defines distributed generation as the units that is [9]:
  - *not centrally planned.*
  - *today not centrally dispatched.*
  - *usually connected to the distribution network.*
  - *smaller than 50-100 MW.*

- IEEE defines DG as ***"the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system"*** *[18]*

DG Definitions

- The International Energy Agency (IEA) defines distributed generation as "***units producing power on a customer's site or within local distribution utilities, and supplying power directly to the local distribution network*"**. [18]

- The California Public Utility Commission (CPUC) defines distributed generation as ***"Generation, storage, or DSM devices, measures and/or technologies that are connected to or injected into the distribution level of the T&D grid and located at customer's premises on either side of meter or at other points in distribution system, such as utility substation".*** [17]

DG Definitions

- Chambers (2001) defines distributed generation as ***"the relatively small generation units of 30MW or less that are sited at or near customer sites to meet specific customer needs, to support economic operation of the distribution grid, or both".*** [18]

- Dondi et al. (2002) define distributed generation as ***"a small source of electric power generation or storage (typically ranging from less than a kW to tens of MW) that is not a part of a large central power system and is located close to the load".*** [18]

- Ackermann et al (2001) define a distributed generation source as ***"an electric power generation source connected directly to the distribution network or on the customer side of the meter".*** [18]

Why Using DGs?

- There are two major factors that drive and contribute to the increasing interests in distributed generations [11]:
  - ***Electricity market liberalization:***
    - Distributed Generation sources provide good flexibility and adaptation to the changes in the economical environment due to their short construction lead time and small size.
    - Distributed Generation technologies can help suppliers to fill in the slots in the liberalized market and provide electricity services as required by the customers.
  - ***Environmental aspects and concerns:***
    - Electricity markets are forced by environmental regulation towards new clean energy sources thus increase interests in renewable based DGs.
    - Distributed generations provide optimum solution for energy consumptions especially for facilities with large demand for heat and electricity.

Electricity Market Liberalization

Peak Power Shaving

- This is considered the major driver for distributed generation installation in US.
- Distributed generation contributes in avoiding electricity price fluctuations.
- They provide a flexible reaction in evaluating electricity prices.

Power Quality

- Distributed generation can assist in solving power quality problems, such as voltage sags, as installation of a DG increase the voltage level in the network.
- Distributed generation can also contribute in the power factor correction.

Reliability

- Network reliability is considered the second major driver for installing distributed generation in US.
- Reliability of the power supply is a very important issue for industrial customers that may direct their investments in installing local distributed generation facilities to increase their reliability levels.
- Two technologies have been specifically identified by the IEA (2002) [11] to contribute in the prevention of power supply interruption.
  - Combined backup system with an UPS unit.
  - Fuel Cells
- For start-up time covering, Combined gas-and-diesel engine with flywheels systems have been commercially available.

Expansion (or Local Network Use) Alternatives

- Distributed generation substitutes or bypasses the costs for transmission and distribution systems expansions.
- Increasing distributed generation units installations can contribute to associated generation requirement problems such as increasing fuel transportation costs.
- About 30 % savings in electricity costs can results from on site generation. [6]
- Distributed generators can operate in stand alone mode thus provide an alternative to connecting customers to grid. This can result in about 6.8 % reduction in grid losses and 10 – 15 % saving in network costs [4, 11].

Grid Support

- Distributed Generation contributes in limiting and/or preventing the installation of auxiliary services to provide a stable and sustained grid operation without contributing in supplying customers.

- As an example of such services, installing external devices (voltage regulators) to regulate network voltages during disturbances.

- Inverter-based distributed generations can provide this functionality despite of the operating conditions.

Environmental Aspects and Concerns

Efficient Use of Cheap Fuel

- Increase opportunity of using cheap fuels, e.g. burning landfill gases when distributed generation facilities are installed near landfills.
- Allow the utilization of costless fuels such as wind, water, and solar for renewable-based distributed generation.

Combined Electricity and Heat Generation

- Using Combined Heat and Power (CHP) units allows cogeneration of heat and electricity. This is very effective, especially at location where there is a continuous heat demand, rather than generating heat separately and obtaining power from the grid.
- CHP units increases the energy conservation 10 – 30 % depending on the unit's efficiency and rating.
- Microturbines have very low efficiency (25 – 30 %) when used for electricity generation only. This efficiency is increased to about 60 % when used as a CHP unit.

IEA Drivers for DGs

The IEA identified five major factors that contribute to the increasing interest in distributed generations:

- Electricity market liberalization.
- Developments in DG technology.
- Constraints on the construction of new transmission lines.
- Increased customer demand for highly reliable electricity.
- Environmental concerns

CIRED Drivers for DGs

Based on a questionnaire for 17 countries, the International Conference on Electricity Distribution (CIRED) survey identified the key drivers for encouraging distributed generation by the following [7]:

- Reduction in gaseous emissions.
- Deregulation or Competition policy.
- Diversification of energy sources.
- Energy efficiency or rational use of energy.
- National power requirement.

CIGRE Drivers for DGs

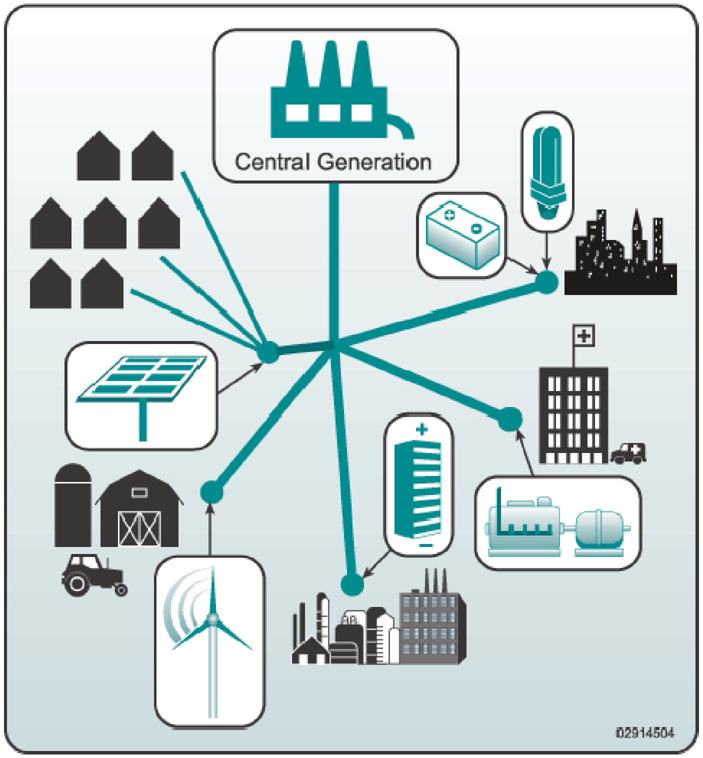
The International Council on Large Electric Systems (CIGRE) report identified additional drivers for encouraging distributed generation, rather than those listed by CIRED, by the following [7]:

- Availability of modular generating plant.
- Ease of finding sites for smaller generators.
- Short construction times and lower capital costs of smaller plant.
- Generation may be sited closer to load, which may reduce transmission costs.

Distributed Generation Characteristics

Power rating categories of DG

Micro DG: < 5 kW
Small DG: 5 kW - 5 MW
Medium DG: 5 MW - 50 MW
Large DG: 50 MW - 300 MW



Distributed Power Generation

Main characteristics

- Geographically dispersed.
- Low installed capacity.
- Renewable or low emission energy sources as primary energy.
- Cogeneration and new technologies.
- Not centrally planned.

Advantages

- Reduces dependence on major power plants.
  - No need to erect new big power generation
  - Deferral of new capacity
- Reduces dependence on long-distance national transmission grid (releasing transmission lines capacities).
  - Avoid cost of new transmission lines
  - Reduce transmission congestion
- Reduces transmission and distribution line losses.
- Reduces environmental impacts and greenhouse-gas emissions.
  - Most DG are renewable or low emission generators

Advantages

- Reduces price volatility in energy markets.
- Enhances or preserve system reliability.
  - Having back-up generation
- Deferral of new capacity (postpone upgrading the T&D infrastructure).
- Enhances flexibility for system operators.
- Accelerates retirement of old units.

Advantages

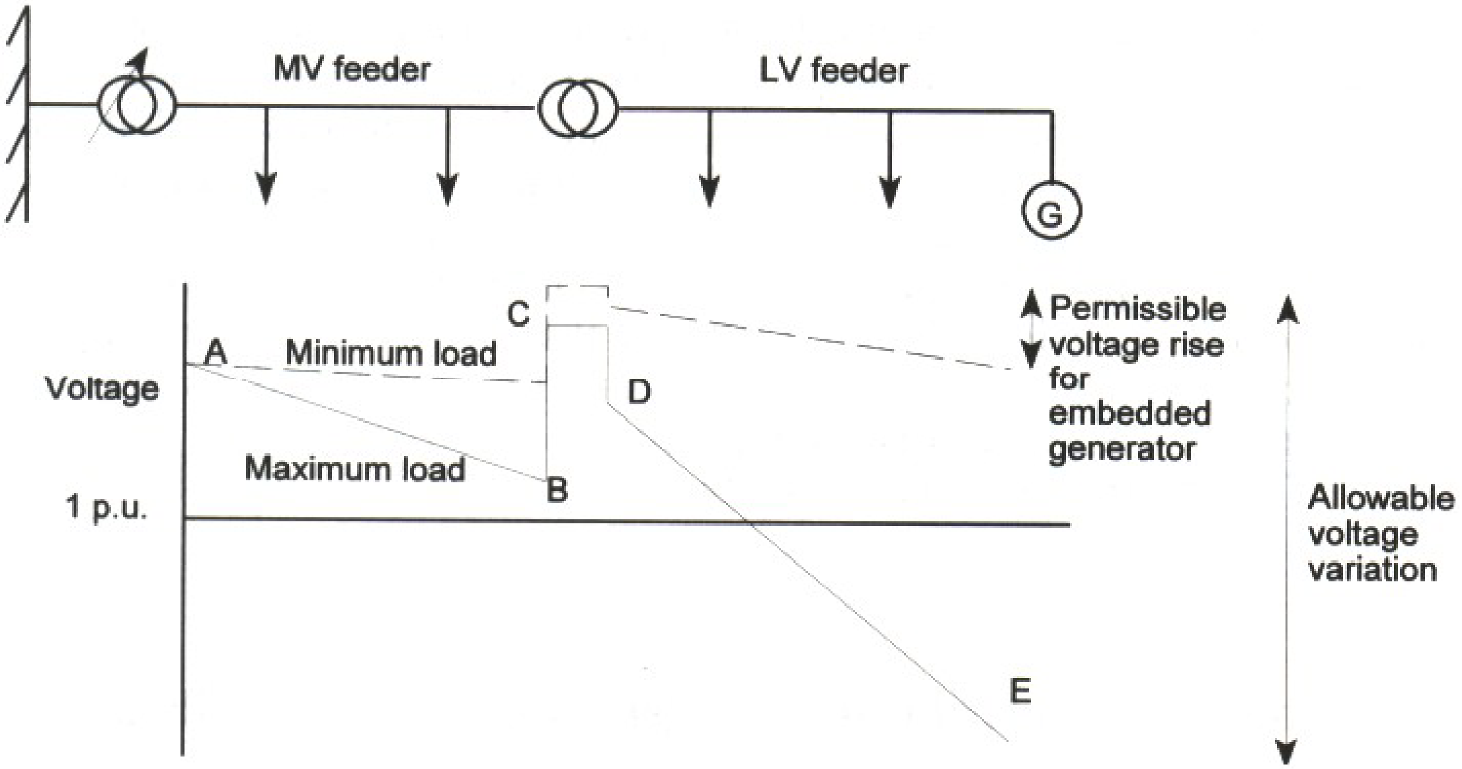
- Increases energy security.
  - Diversifying energy sources and reducing dependence on complex large systems
- Increases personal, business and regional self-sufficiency.
- Well adapted to alternative and renewable energy sources

Impacts of DGs on Distribution Systems

Network Voltage

- Voltage profile along distribution systems is greatly altered with the installation of distributed generation.
- The DG capacity is dependent on the maximum allowable voltage variation level and the voltage level at minimum loading conditions.
- Distributed generation may also cause a voltage dip when consuming reactive power from the grid as in the case of induction generator based DGs (used for wind generation).

Voltage Profile along a Radial Feeder [7]


MV feeder
LV feeder
G
Voltage
1 p.u.
A
Minimum load
Maximum load
B
C
D
E
Permissible voltage rise for embedded generator
Allowable voltage variation

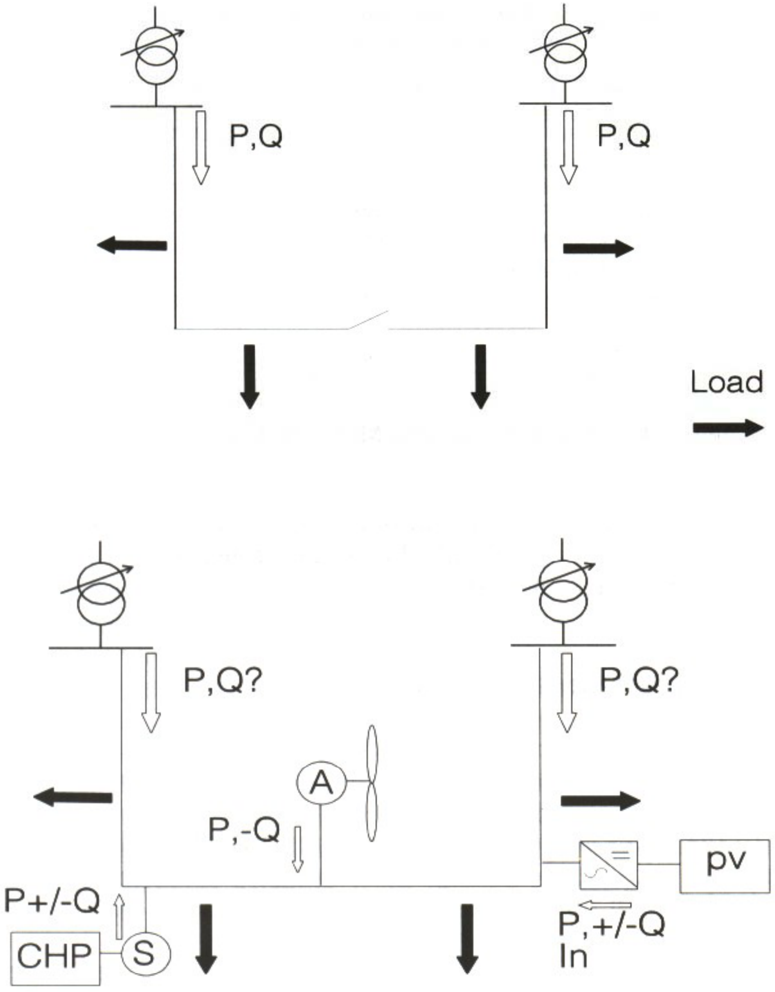
A	voltage held constant by tap-changer of distribution transformer
A–B	voltage drop due to load on MV feeder
B–C	voltage boost due to taps of MV/LV transformer
C–D	voltage drop in MV/LV transformer
D–E	voltage drop in LV feeder

Design Rules for Distributed Generation [7]

Network Location	**Maximum DG size**
Out on 400 V network	*50 kVA*
At 400 V busbar	*200 – 250 kVA*
Out on 11 kV or 11.5 kV network	*2 – 3 MVA*
At 11 kV or 11.5 kV busbar	*8 MVA*
On 15 kV or 20 kV network and at busbar	*6.5 – 10 MVA*
On 63 kV to 90 kV network	*10 – 40 MVA*

Power Flow

- Distribution systems become active systems not passive.
- Voltage levels and power flow is determined by the generation and the penetration level of distributed generation.
- Distributed Generation units always generate active power but they can generate or absorb reactive power.
- DG installation may result in reverse power flow.



Source: Embedded Generation [7]

Power Quality

- Power electronic interface-based DGs inject harmonic currents to the utility grid that cause voltage disturbance that may exceed the permitted limits.
- Direct connected generators based DGs reduce the harmonic voltages in the grid.
- Connection and disconnections of DGs cause large changes in networks currents that result in transient voltage variations.
- Constant speed wind turbine-based DGs cause cyclic fluctuation in the generated power. This results in current flicker.
- Power quality of sensitive plants can be improved by installing a local generating units.

Network Fault Levels

- Most types of distributed generation (Rotational based DG) contribute in increasing the fault level of the distribution network.
- In some cases, the increased fault level may exceeds the switchgears rating especially in rural areas.
- Increasing the fault level with the presence of DGs can be diminished by inserting an impedance between DGs' generators and the network. However, this result in an increase in the voltage variation and system losses.

Protection

- Embedded generation installation in distribution systems add several complications to the existing protection schemes.
  - Generators’ protection from internal faults occurrence.
  - Generators neutral grounding.
  - Islanding or Anti-islanding operation of distributed generation when main supply is disconnected.
  - Protecting the faulted section of the system from the fault current fed from connected distributed generations.
  - Injected fault current from DGs support the system voltage and may cause relays under reaching.

Stability

- Transient stability issues are of important consideration if DGs are considered as a constant support of active power to the network.
- When using ROCOF (Rate Of Change Of Frequency) relays and during major network disturbances, they may cause inaccurate trip of large numbers of DGs leading to more depressed system frequency.
- Induction generators-based DGs draw large reactive currents when over-speed during transient instability. This cause more drop in the network voltage and voltage instability.

Distribution Network Operation

- Distribution network with embedded distributed generation can be energized and supplied from more than one point.
- Safety regulations and policies for workers are affected.
- Reducing flexibility due to difficulty resulting in obtaining outage for planned maintenance.

Economical Issues

- Distributed generation affects distribution systems losses and consequently have impacts on the operating costs of distribution networks.

- Currently, most DGs are operated at unity power factor, thus they have no impacts on the costs of generated reactive power. There are some cases (Denmark) at which embedded generations operate at different PFs and affect the operation costs.

- In the future, it is believed that DGs will contribute in the generated reactive power. Consequently, DGs will have direct impact on reactive power costs and the total operating costs of distribution networks.

Impacts of DGs on Transmission Systems

- Power flow is affected.
- Reducing transmission system losses.
- Reducing transmission conggestion
- Reducing transmission systems operating charges.
- Reducing requirements for asset especially in highly meshed networks.

Impacts of DGs on Central Generation Plants

- Reduces the net generated power from central generation plants. This might affect the generation cost either positively or negatively.

- Generated power from some types of distributed generation are very difficult to be predicted. This results in increasing the uncertainty in the generation scheduling.

- DG installation will affect the central plants generation cost specially the start up and fuel saving cost.

Impact of DG on Personnel Safety

- Distributed generations alter the power flow in distribution networks both during normal operation and under fault conditions.
- Utility workers have to be aware of all DGs locations to ensure disconnecting or isolating them before performing repairs and maintenance.
- DGs locations should be identified on office maps and records as well as on fields switching equipment.
- Utility safety procedures require the existence of a visible and lockable open breaker (disconnect switch) at the DGs locations that is accessible by the utility personnel at all times to disconnect DGs before working in the grid.

Islanding Impacts

- Remaining online (connected) for DGs in case of utility outage could result in:
  - Overloading of the DG units when trying to supply the utility loads.
  - DGs will be out of phase when re-establishing the interconnection.
- DGs must be disconnected from the utility grid in case of loss of utility supply to avoid any damage to the DG unit and provide safe operating conditions for utility workers.
- DGs should remain disconnected until the utility system is restored.
- Synchronizing equipment have to be provided to maintain and / or establish synchronization with the utility before reconnecting DGs to re-energized utility grid after an outage.

Distributed Generation Classification

Distributed Generation Technologies

Renewables

- *Wind Power*
- *Solar Photovoltaic*
- *Small Hydro Power*
- *Biomass*
- *Tidal Energy*
- *Waver Energy*
- *Geothermal*

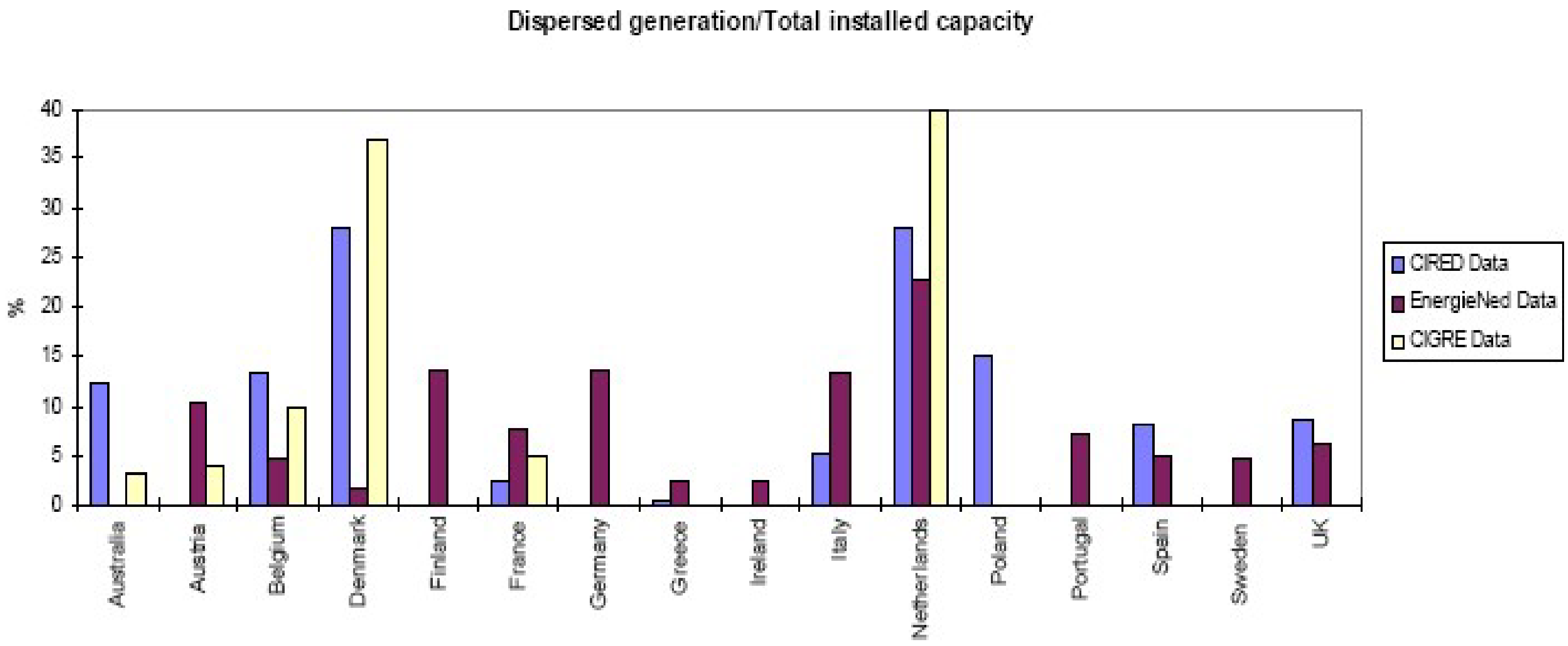
Non-Renewables

- *Reciprocating Engine*
- *Micro-turbine*
- *Fuel Cell*

Storage Devices

- *Super-conducting magnetic energy storage (SMES)*
- *Battery energy storage system (BESS)*
- *Flywheel*
- *Ultra-capacitors*
- *Modular pumped hydro*

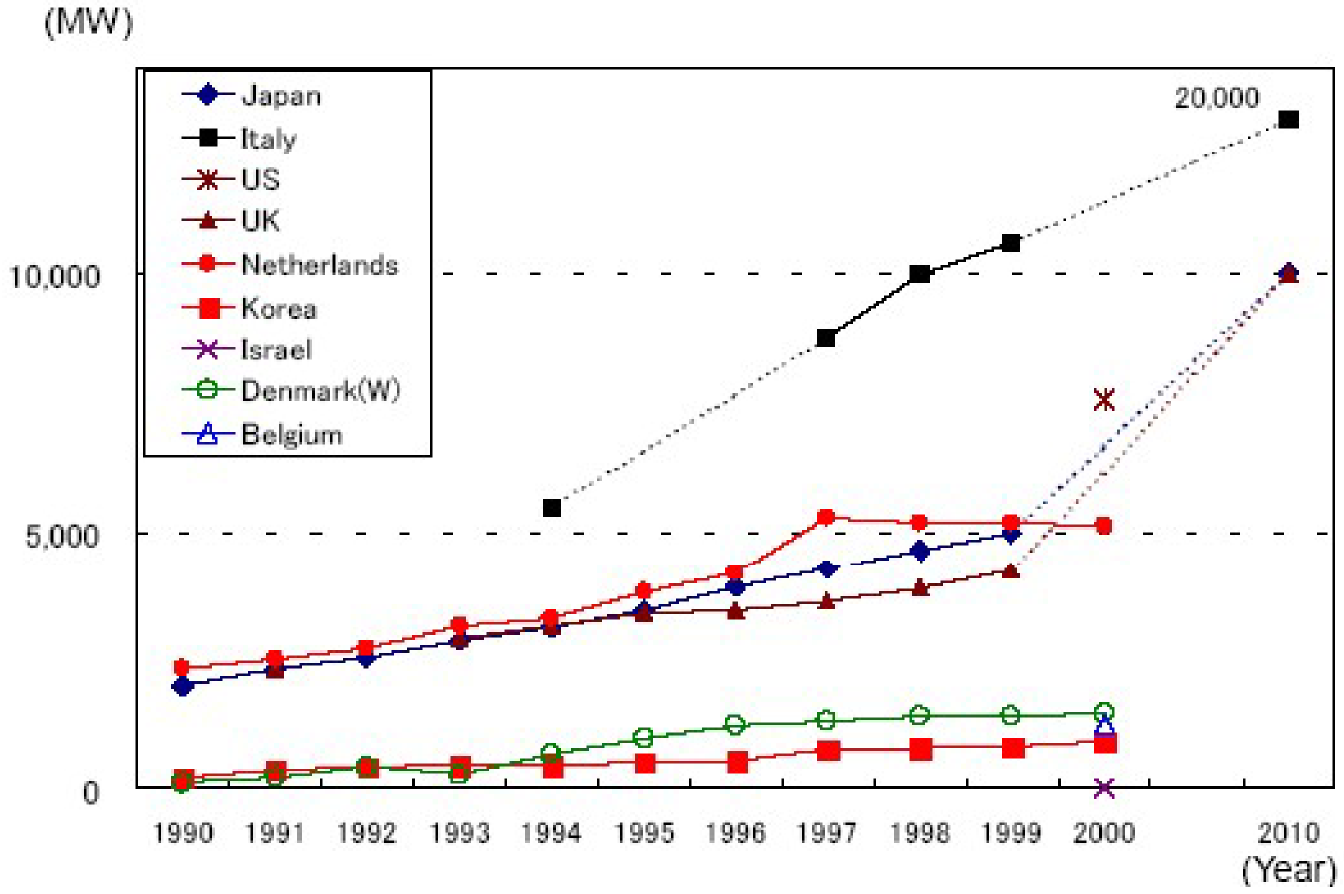
Global Installed Distributed Generation



Global installed distributed generation [3]

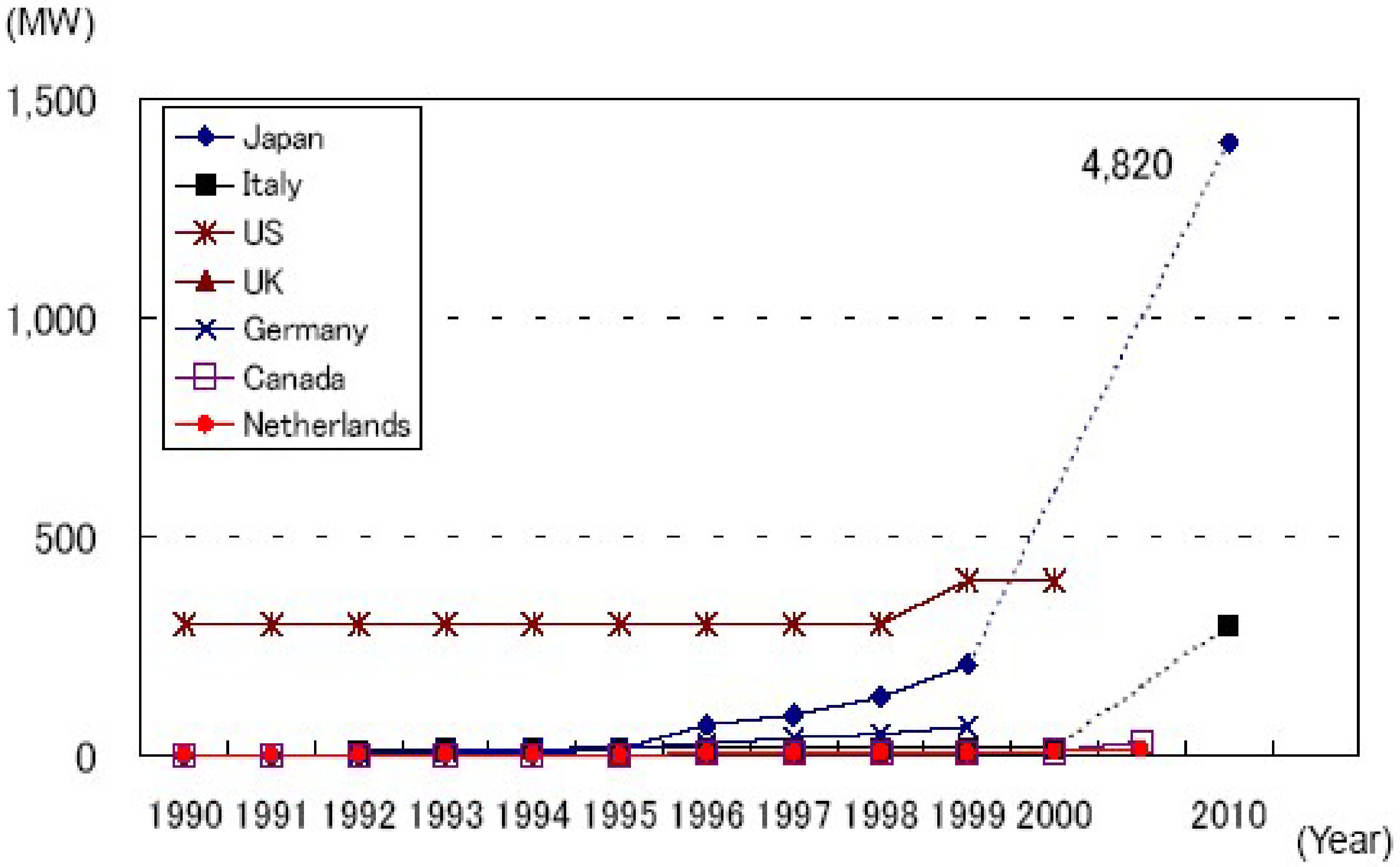
Sustainable Distributed Generation *(ECE 667)*

Global Cogeneration Power Generation



Global cogeneration power generation progress and prediction [9]

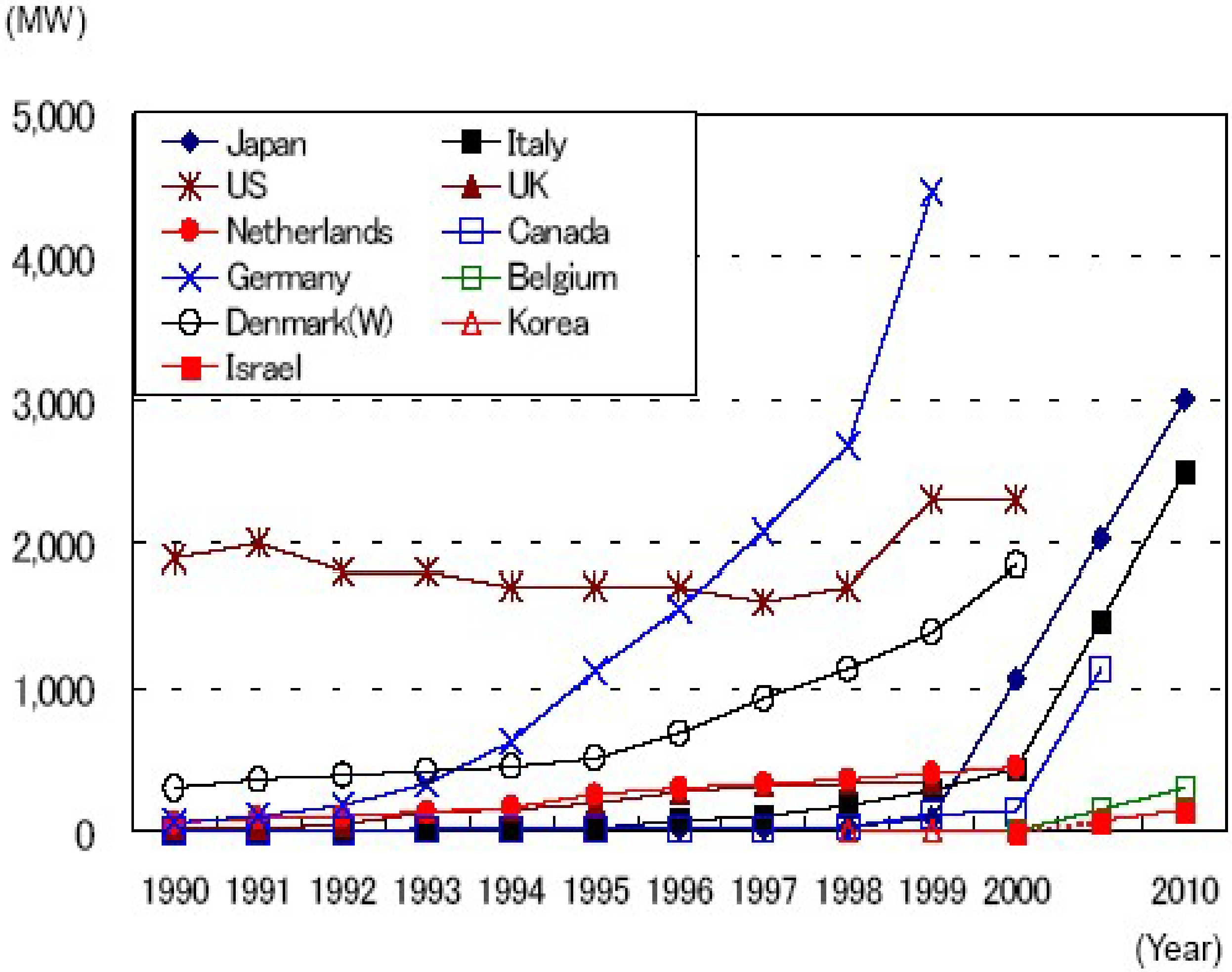
Global Solar Power Generation



Global solar power generation progress and prediction [9]

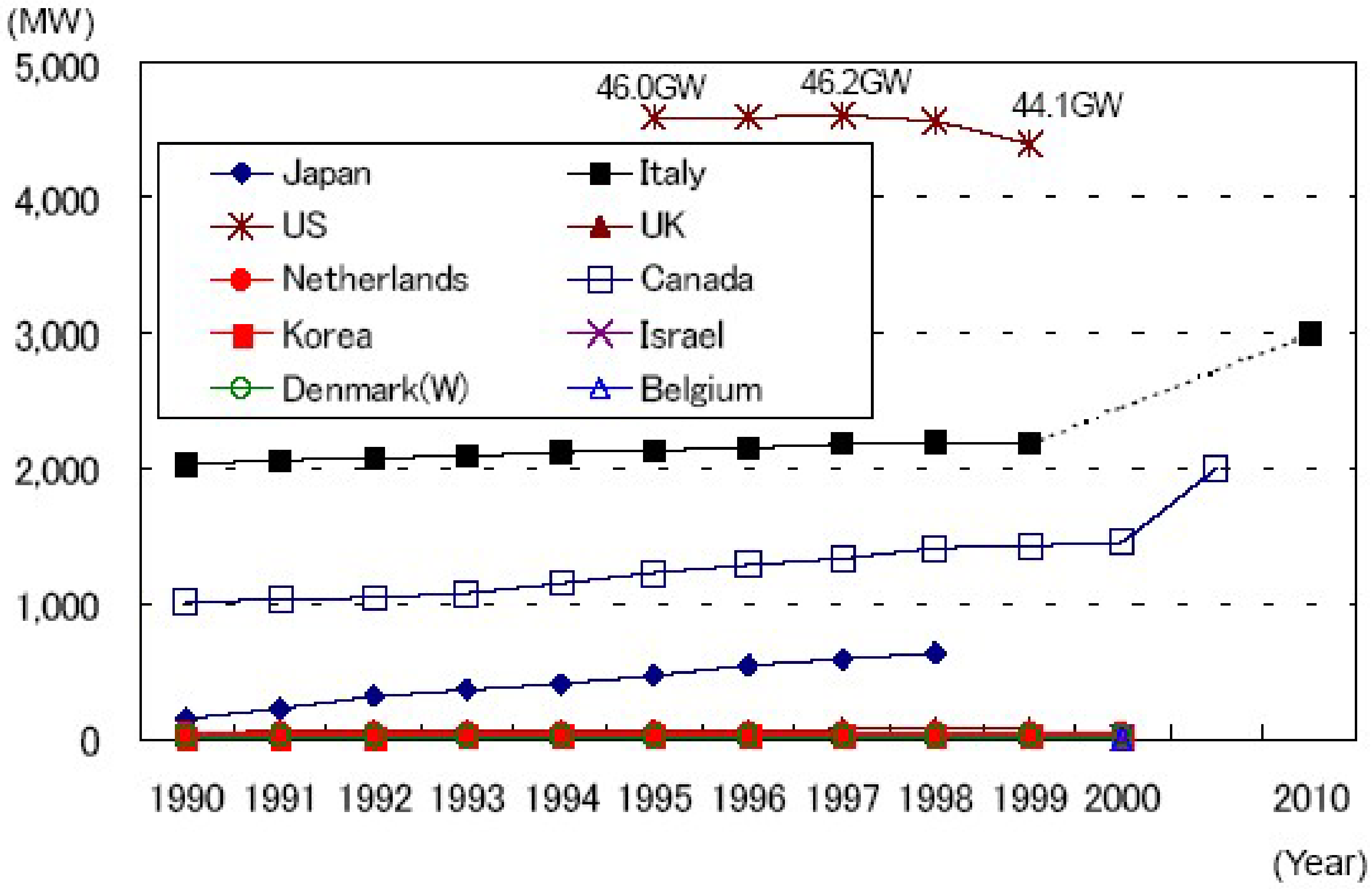
Sustainable Distributed Generation *(ECE 667)*

Global Wind Power Generation



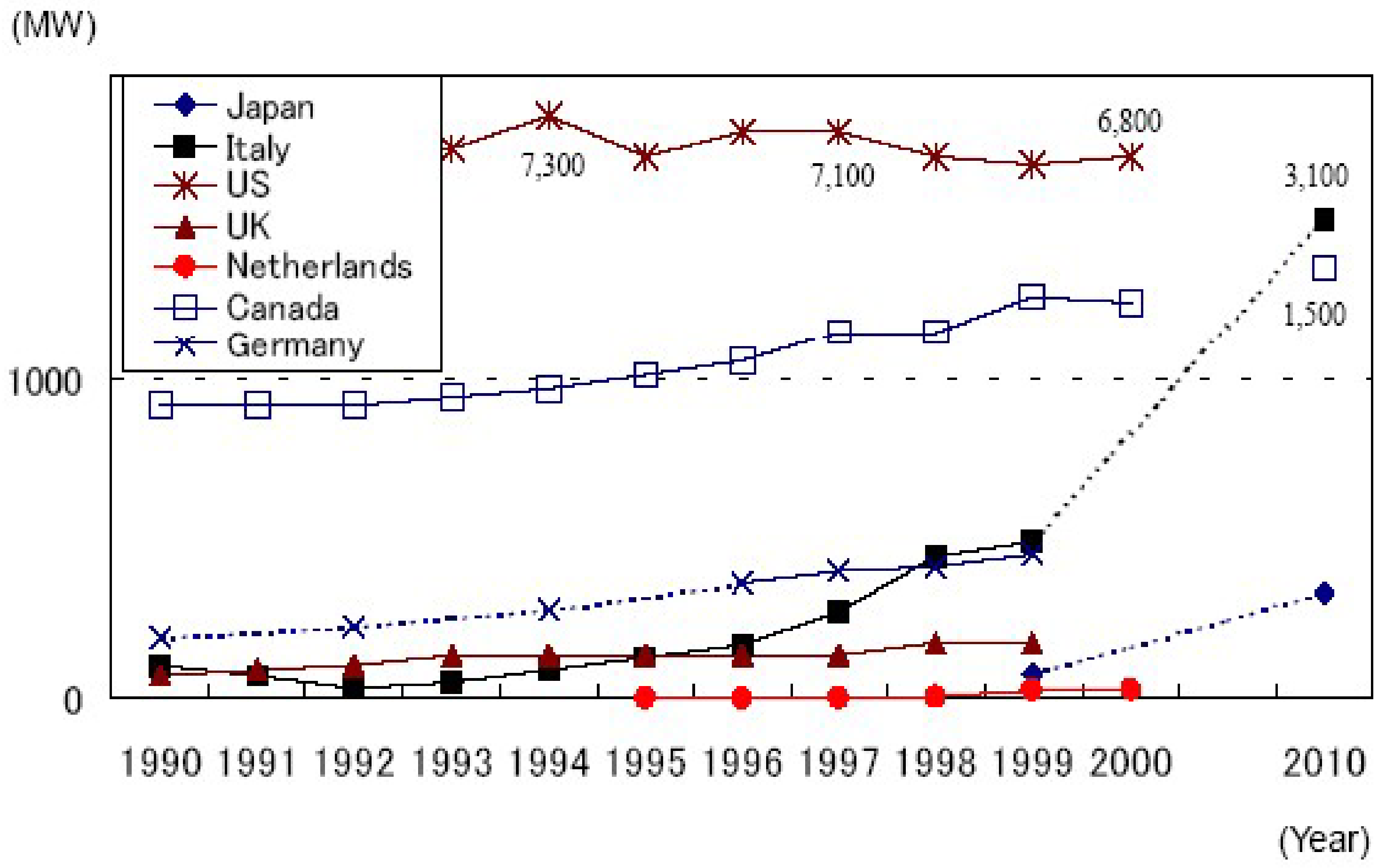
Global wind power generation progress and prediction [9]

Global Small-Hydro Power Generation



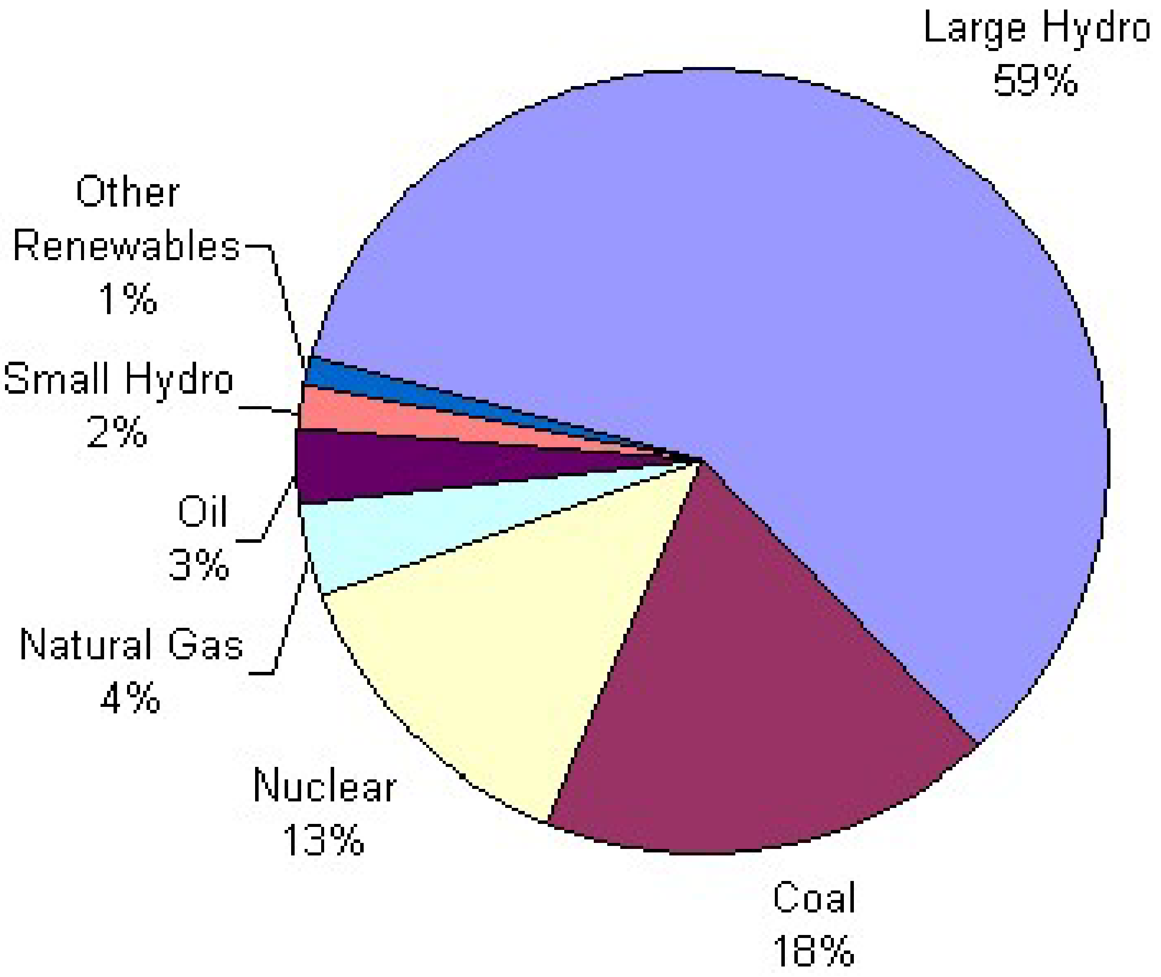
Global small-hydro power generation progress and prediction [9]

Global Biomass Power Generation



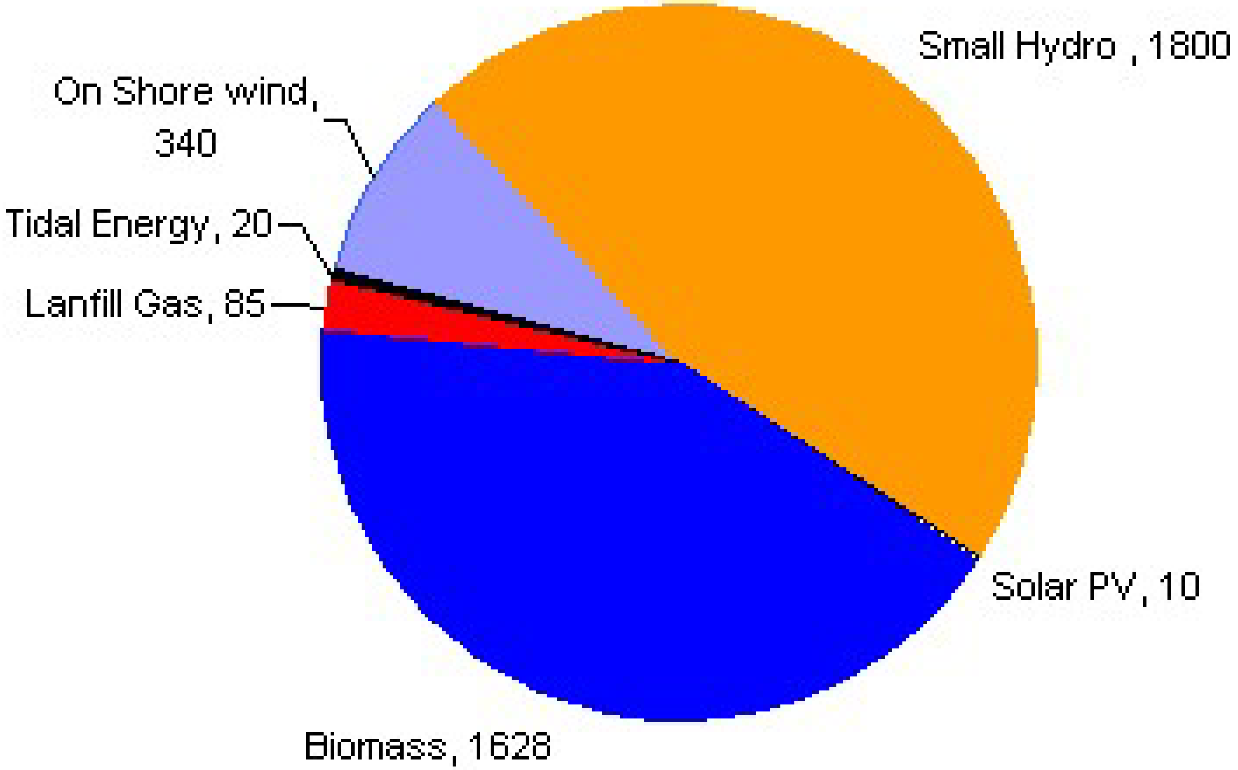
Global biomass power generation progress and prediction [9]

Electricity Generation in Canada



Electricity generation in Canada at 2003

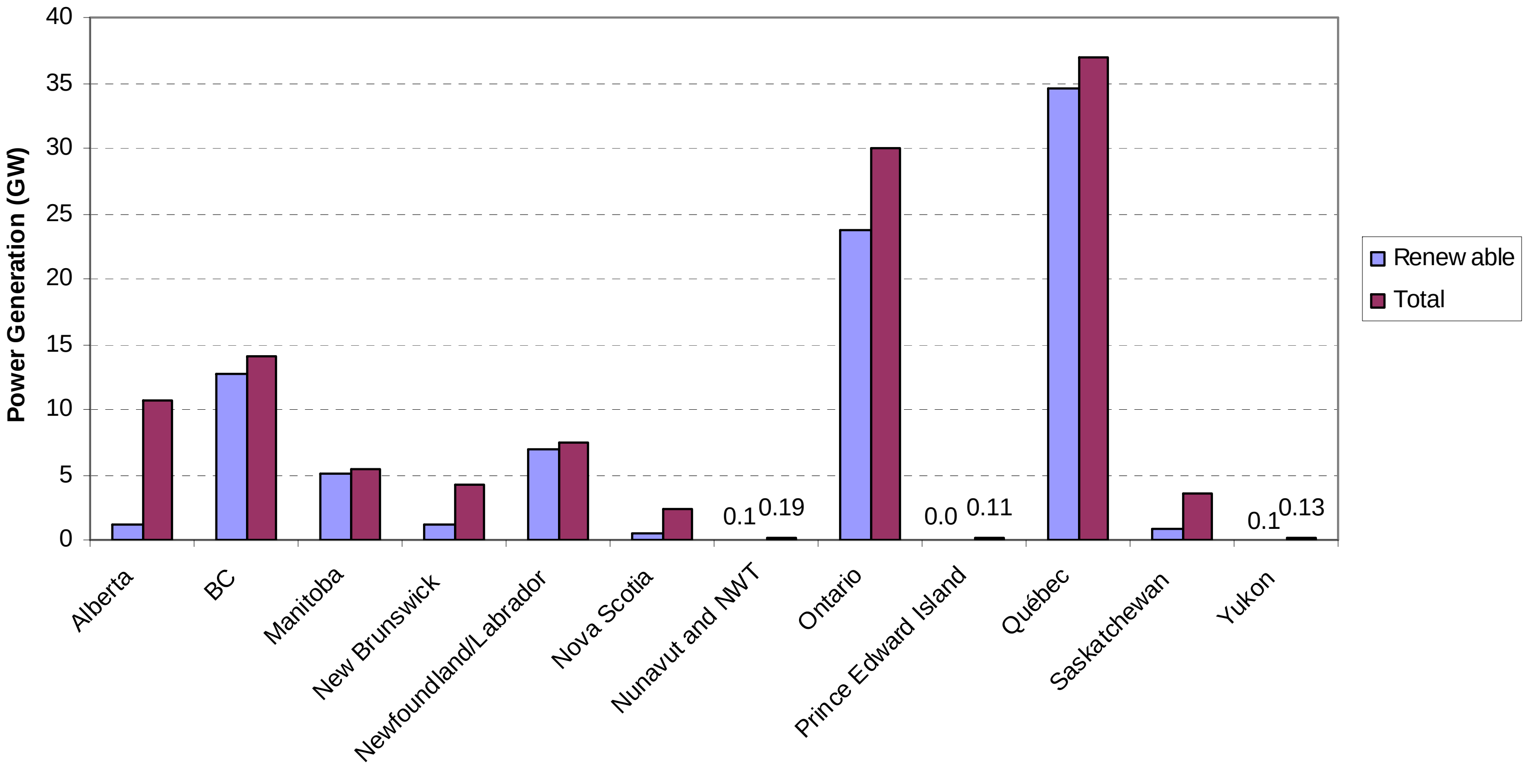
Renewable Energy Generation in Canada



Renewable energy generation (MW) in Canada at 2002

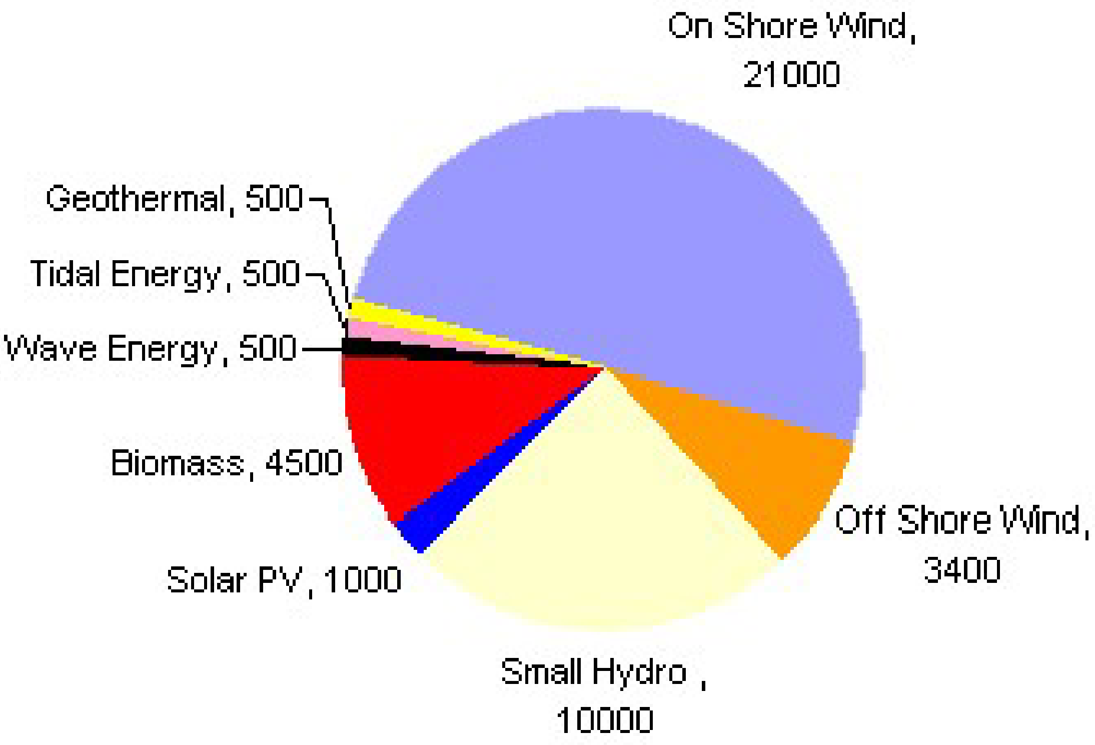
(with the exception of large hydro generation)

Renewable Energy Generation in Canada



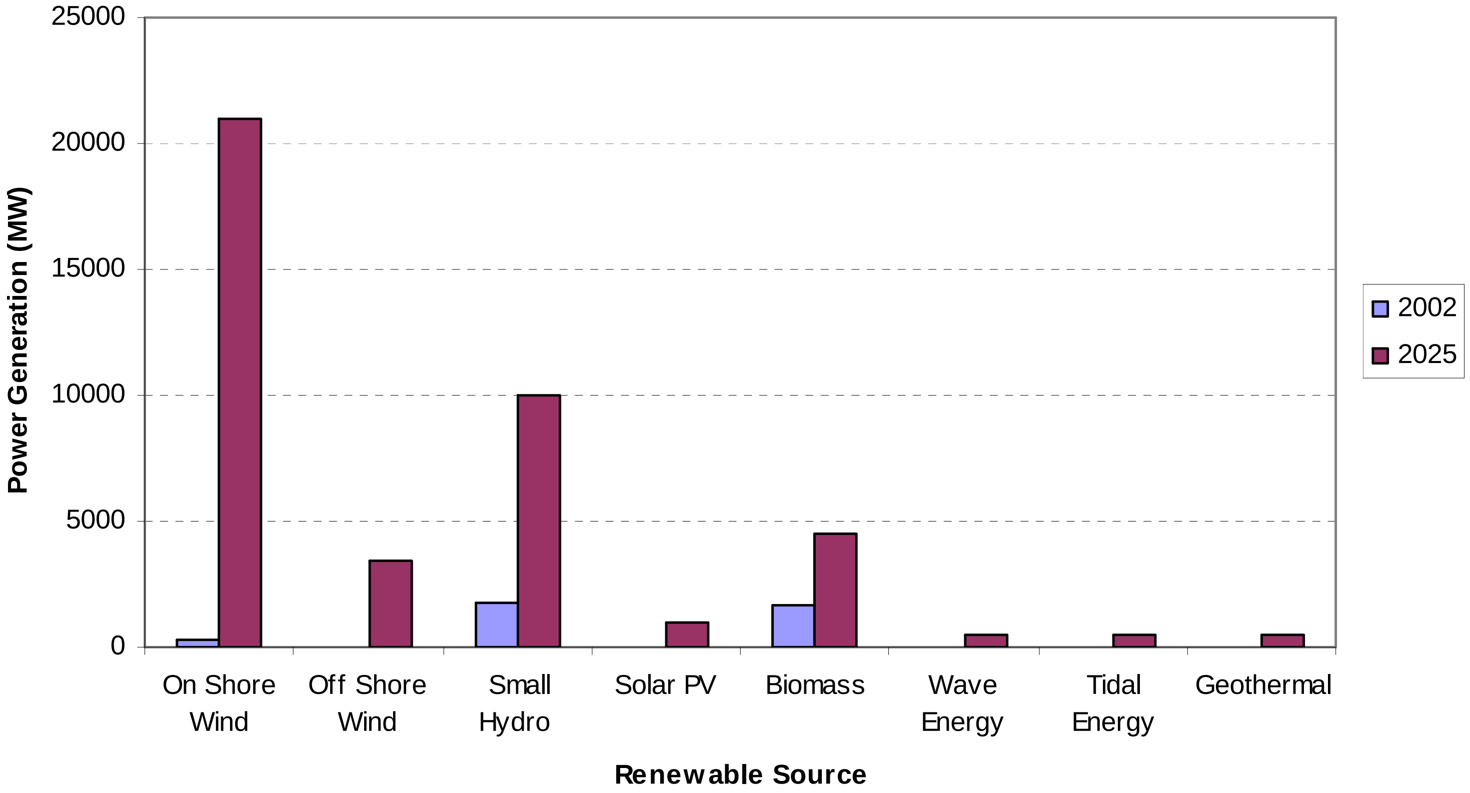
Renewable energy generation (GW) in the Canadian provincial and territorial, 2003.

Green Power Potentials in Canada



Predicted Green Power Generation (MW) in Canada at 2025

Green Power Predicted Progress in Canada



Predicted Progress in Green Power Generation in Canada

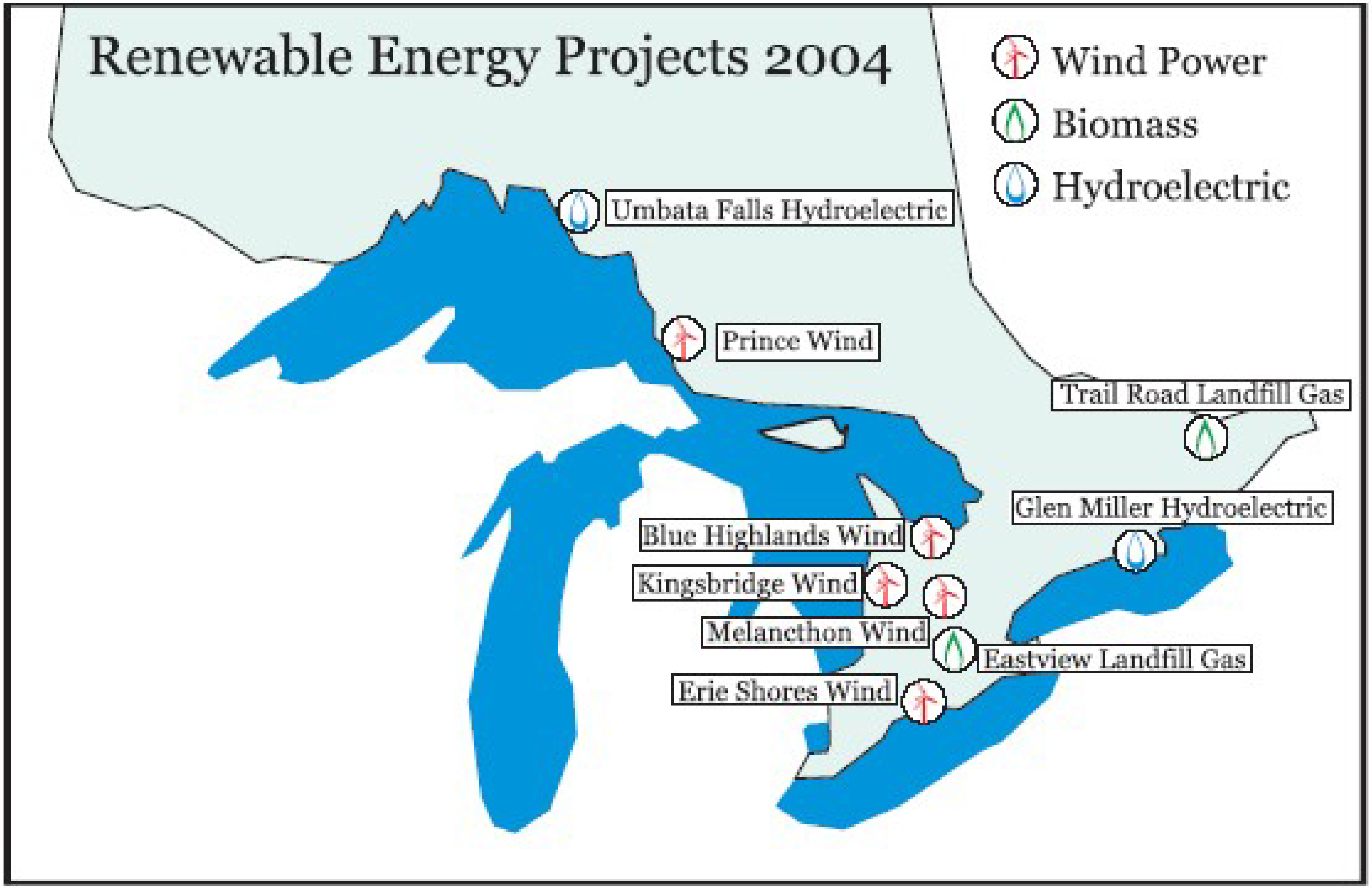
Ontario RFPs for Green Energy

Renewables I

- The Canadian Government announced a Request For Proposals (RFP) on April 2004 for 300 MW of new renewable energy supply.
- This opened the door to new, clean, renewable energy sources such as wind, solar, water, biomass and landfill gas.
- Forty-one projects were proposed as a response to the RFP.
- The Government announced ten accepted proposal on November 24, 2004.
- The accepted projects will provide Ontario with 395 MW of green power with an estimated new investment of $700 million.

- The *Renewables I* RFP Projects include:

Project	**Location**	**Rating (MW)**	**Company / Cooperation**
Eastview Landfill Gas: Energy Plant	Guelph	2.5	Guelph Hydro Generation Company
Erie Shores Wind Farm	Port Burwell	99	Erie Shores Wind Farm L.P
Kingsbridge Wind Power Project	Goderich	39.6	EPCOR Power Development Corporation
Melancthon Grey Wind Project	Shelburne	67.5	Canadian Hydro Developers, Inc
Prince Wind Farm	Prince Township, near Sault Ste. Marie	99	Superior Wind Energy Inc
Blue Highlands Wind Farm	Blue Mountains	49.5	Superior Wind Energy Inc
Trail Road Landfill Gas Generating Station	Ottawa	5	Energy Ottawa
Umbata Falls Hydroelectric Project	on White River, near Marathon	23	Partnership of the Pic River First Nation and Innergex II Income Fund
Glen Miller Hydroelectric Project	Trenton	8	Innergex II Income Fund
Hamilton Digester Gas	Hamilton	1.6	Hamilton Community Energy


Renewable Energy Projects 2004
Wind Power
Biomass
Hydroelectric
Umbata Falls Hydroelectric
Prince Wind
Trail Road Landfill Gas
Glen Miller Hydroelectric
Blue Highlands Wind
Kingsbridge Wind
Melancthon Wind
Eastview Landfill Gas
Erie Shores Wind

Projects for Renewables I RFP [12]

2500 MW RFP

- The Canadian Government announced a Request For Proposals (RFP) early 2004 for 2,500 MW of new clean generation and demand-side projects.
- This 2,500 MW generation represents 1/3 of the government's commitment to replace coal-fired generation with cleaner sources.
- Thirty-three projects were proposed as a response to the RFP representing about 8,800 MW.
- The Government announced six accepted projects.
- The accepted projects will provide Ontario with 2,235 MW which is enough power for over 850,000 homes with an estimated new investment of $1.5 billion.

- The *2500 MW* RFP Projects include:

Project	**Location**	**Rating (MW)**	**Type**
Greenfield Energy Centre	Sarnia-Lambton	1005	Combined cycle gas-fired generation
St. Clair Power	Sarnia-Lambton	570	Combined cycle gas-fired generation
Greenfield North Power Project	Mississauga (Hurontario Street, north of Derry	280	Combined cycle gas-fired generation
Greenfield South Power Project	Mississauga (Loreland Avenue, south of Mattawa Avenue)	280	Combined cycle gas-fired generation
Greater Toronto Airports Authority	Mississauga	90	Cogeneration
Loblaw Properties	-	10	Demand response project

Renewables II & III

- Two Renewables RFPs were announced by the Government on April 19, 2005 (*Renewables II & Renewables III*).
- *Renewables II* was issued in draft on April, 22, 2005 and in its final form on June, 17, 2005, while *Renewables III* was issued in draft on July 12, 2005.
- *Renewables II* calls for up to 1,000 MW of new renewable energy sources ranging between 20 MW and 200 MW.
- *Renewables III* calls for up to 200 MW of new renewable energy sources ranging between 250 kW and 19.9 MW.

Overview of DG Interfacing Equipment

Interface Types

- Generally, DG are interconnected with the utility to operate in parallel with the distribution system. The main types of the electrical system interfaces are:

1. ***Rotating Machines***
    - Synchronous machines.
    - Asynchronous (induction) machines.
2. ***Power Electronic Converters***.
3. ***Combined Induction Machines and Power Electronic Converters***
4. ***Other Components:***
    - Transformers and Grounding System

Synchronous Machines

◆ First type of electric machines used for backup generation applications.

◆ The majority of distributed generation interconnected with the utility distribution system utilize three phase synchronous machines (wind, Hydro, and ICE). However, power electronic converter might be combined to facilitate energy processing.

◆ The machine with its inherent inertia can follow any load change with proper field and governor control.

◆ Synchronous-based distributed generations usually operate with constant var (reactive power) exciter control unless the machine is large relative to system capacity (in case of islanding or stand alone operation).

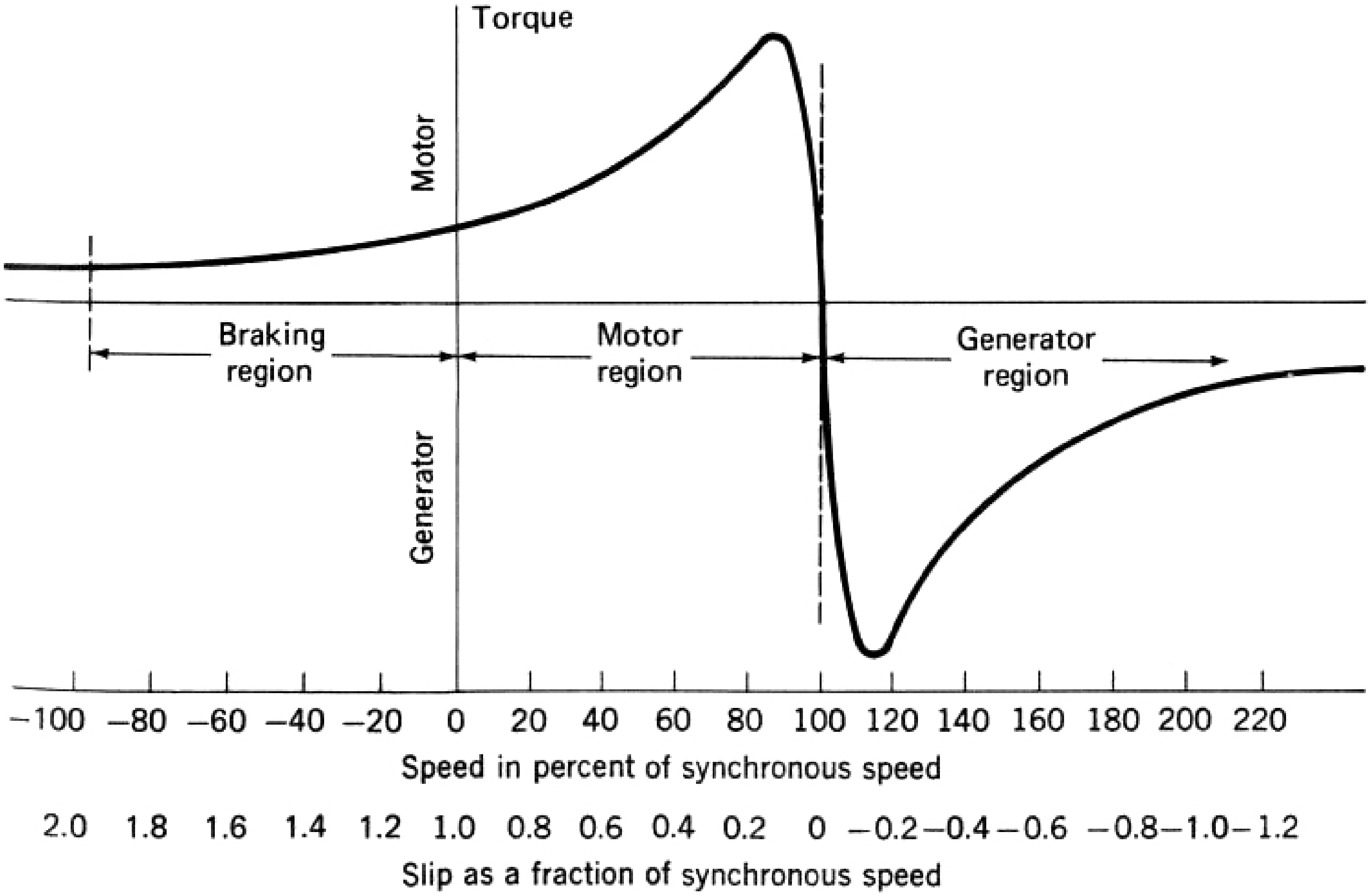
- A large DG can regulate the utility system voltage to improve the voltage profile across the distribution feeders.
- This is considered a power quality advantage in weak systems. However, these generators should be coordinated with the utility voltage regulators and protection equipment to avoid any operating conflicts.

Asynchronous (Induction) Machines

- Simple to interface to the utility as no special synchronizing equipment is required.
- They are often started as a motor using the utility power line.
- Induction generators are typically smaller than 500kW (5MW is available now) and they suitable for wind DG.
- Induction generators are induction motors driven slightly faster than synchronous speed.
- Unlike synchronous generators, Induction generators are capable only of producing active power and not reactive power.

- They need reactive power from the power system to which it is connected to provide excitation. This might affect the utility voltage and result in a low-voltage problem.
- Capacitors are then added to supply the reactive power to avoid a low-voltage problem.
- They can be started across the line if the capacity of the power system permits.
- For weak systems, the prime mover is started and brought to near synchronous speed before the machine is interconnected.

Torque-Speed Characteristic



Other Types of Generators

- High Voltage Generators (HVG), Switch Reluctance Generators (SRG), and Transverrse Flux Generators (TFG) are considered for as possible candidate types of generators for future wind turbine industry. Most of these generators' types are still used as prototypes and still under research investigations for wind power generation.

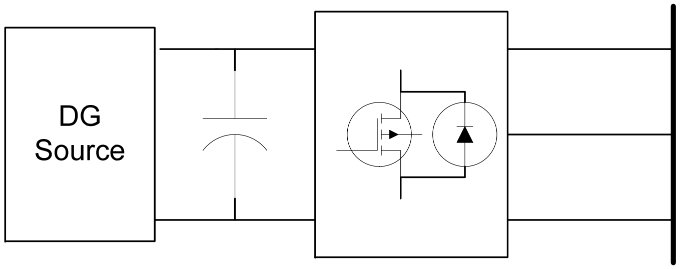
Power Electronic Converters

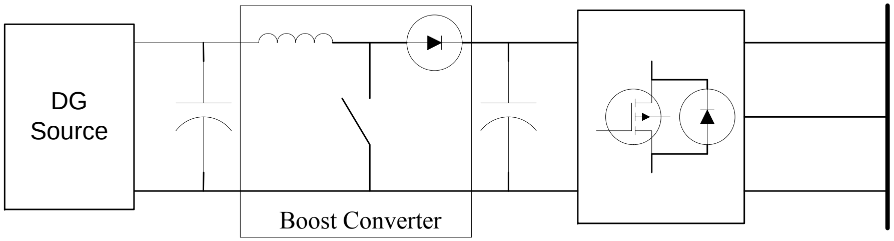
- DG technologies that generate either dc (fuel cells, photovoltaic, and storage batteries) or non-power frequency ac (wind, tidal streams and micro turbines) must use an inverter to interface with the power system.
- An inverter is a solid state device that converts DC or variable frequency AC electricity to AC electricity at a desired voltage and frequency.
- The inverter technology has changed from the early thyristor-based, line commutated inverters to switched PWM inverters using IGBTs and GTO’s.
- This shift in technology has greatly reduced the amount of harmonics injected by these inverters to the utility system.

- They usually, produce power at unity power factor to allow the full current-carrying capability of the switch to be used for delivering active power.
- Furthermore, the inverter interface can be controlled to mitigate the power quality problem of the utility.
- When trouble is detected, the inverter can be switched off very quickly (in milliseconds) unlike the rotating machines which may require several cycles to respond.

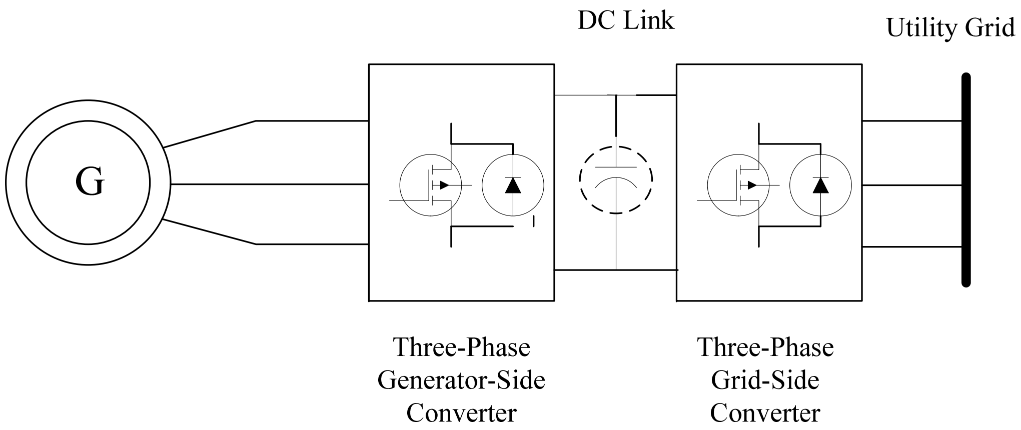
Types of Power Electronic Converters

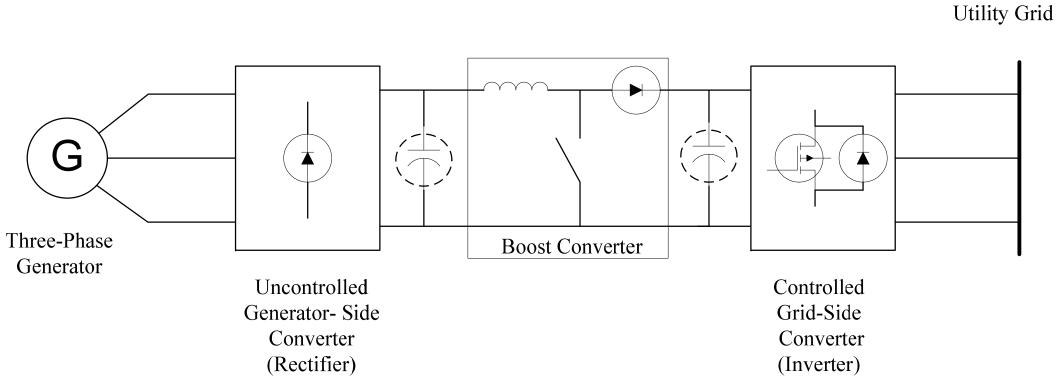
- Distributed generation that generate DC directly can be interfaced with the utility grid by:
  - Direct connection via an inverter (if DC level is acceptable).
  - Connection through a DC-to-DC boost converter and an inverter (if DC level is low such as in fuel cell).


DG
Source
Controlled Converter
(Inverter)


Utility Grid
DG
Source
Boost Converter
Controlled Converter
(Inverter)

- Distributed generation equipped with rotating machines and generate non-power frequency AC can be interfaced with the utility grid by:
  - Back-to-Back controlled Converter.
  - Back-to-Back uncontrolled and controlled Converter with an intermediate DC-to-DC Boost Converter.


DC Link
Utility Grid
G
Three-Phase Generator-Side Converter
Three-Phase Grid-Side Converter


Utility Grid
G
Three-Phase Generator
Uncontrolled Generator- Side Converter (Rectifier)
Boost Converter
Controlled Grid-Side Converter (Inverter)

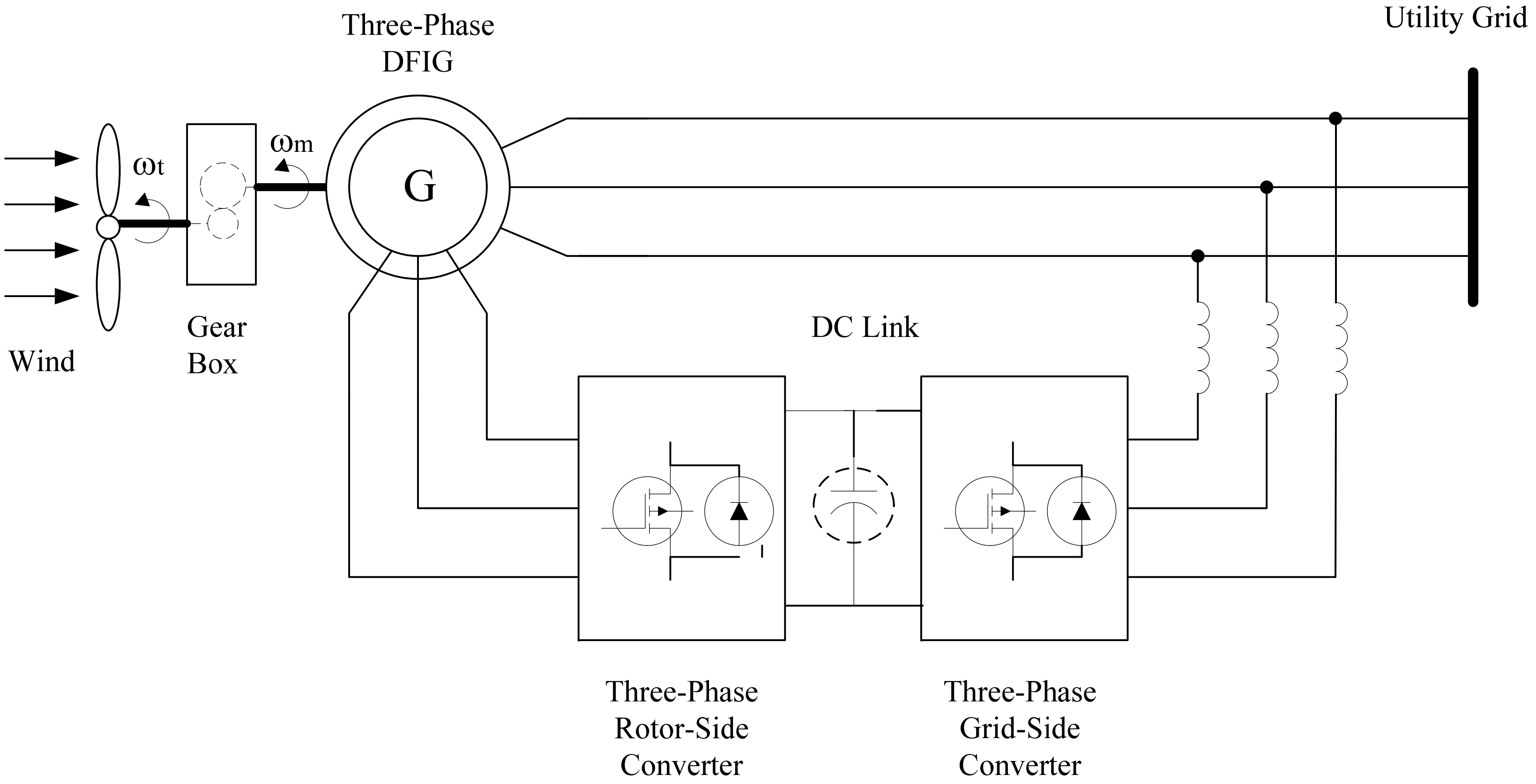
Merits and Demerits

- Power electronic interface provides some advantages such as:
  - Provide wider speed range of operation.
  - Increasing the efficiency of the interfaced rotating machines (in case of power tracking).
- On the other hand, large power electronics interface posses some disadvantages that can be summarized in the following:
  - Higher system capital cost.
  - Increase the system complexity.
  - Increasing electrical losses.
  - Injecting harmonic current into the utility grid.

Combined Induction Machines and Power Electronic Converters

- Known as Doubly-Fed Induction Generators.
- They are wound rotor induction generators where both the stator and the rotor are connected to the utility grid. However, the stator is connected directly, while the rotor is connected via a back-to-back controlled converters.
- DFIGs have several advantages over other wind turbines interface that can be summarized in the following:
  - Dynamic performance capability at sub-synchronous and super-synchronous speed ranges (utilizing converter interfacing allow the machine to operate as a generator for wide speed range).
  - Capability of generating constant frequency active power.
  - Decoupled control of the generated active and reactive power.
  - Less converter ratings are required as they conduct rotor-circuit power only.

DFIG Configuration


Three-Phase
DFIG
Utility Grid
ωt
ωm
G
Wind
Gear
Box
DC Link
Three-Phase
Rotor-Side
Converter
Three-Phase
Grid-Side
Converter

Transformer Configuration and Grounding

- The transformer configuration and grounding of DG interface must be compatible with the utility system to avoid voltage swells and over-voltages that can produce a severe damage to customer and utility equipment.

- In North America, distribution systems are 4 wires multi-grounded neutral systems.

- This arrangement limit the over-voltage on healthy phases to about 1.25 pu to 1.35 pu of the pre-fault condition.

Transformer Configuration and Grounding

- According to IEEE Std., effective grounding means that the zero sequence reactance must be less than 3 times the positive reactance.
- DG that is not grounded properly may cause severe voltage rise during single line to ground faults.
- This over-voltage becomes more dangerous if a generation island is formed and continuously feed certain loads while the utility system is faulted.
- Customers on un-faulted phases are subjected to the worst over-voltage (1.75 pu) for indefinite period which definitely damage both the customer and utility equipment.
- Saturation of distribution transformers will limit this voltage rise to 1.5 which is still dangerous.

Transformer Configuration and Grounding

- To avoid the previous mentioned problems, large capacity DGs that can sustain islands and are connected to the 4 wire multi-ground systems should be:

  - ***Effectively Grounded***.
    - Preferred approach because it limits voltage swells due to faults.

  or

  - ***Use protective relaying to detect faults at the primary side and quickly disconnect DG***.
    - While this approach is used in many installations, sever transient voltages can appear at the customer terminals when the DG is cleared.

Transformer configuration for DG sites

Transformer configuration	**Comments**
Delta / Wye-grounded or Delte / Delta	Do not provide effective grounding
Wye-grounded / Wye-grounded	Provide effective grounding if the generator side meets neutral impedance requirement
Wye-grounded / Delta	Typically provide effective grounding regardless of the generator grounding arrangement.

- One approach to create an effective ground for DG is to use a cascaded grounded transformer bank when the step-up transformer is not providing effective grounding.
- The use of additional transformer bank will reduce the zero sequence current when single line to ground faults occur.

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